Detection of screw threads in computed tomography 3D density fields [⋆]

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Abstract: In this paper, a new method is proposed to automatically detect screw threads in 3D density fields obtained from computed tomography measurement devices. The described method can be used to automate many operations during screw thread inspection process and drastically reduce operator's influence on the measurement process resulting in lower measurement times and increased repeatability.

Keywords: screw thread computed tomography feature extraction

1. INTRODUCTION

Many types of coordinate measurement systems are widely used to inspect parameters of metric screw threads (NPL, 2010). Screw thread measurement using coordinate measuring machines (CMM) is a tedious process which requires high operator's skill. CMM measurements usually aquire a limited set of points suitable for a feature-based inspection, however not enough for an in-depth analysis and assesment of a screw pair fit. This limitation is crucial while dealing with screw threads for mission critical applications (petro-chemical industry, heavy engineering industry et al.). Nowadays, as a result of well-established international practice, the complex inspection of screw threads is performed using thread gauges. Gauges are subject to wear and tear and require regular replacement and inspection which yields expenses.

In this paper, a new method is proposed, allowing to perform feature-based inspection and complex in-depth analysis of screw threads using the date aquired from computed tomography (CT) measuring devices. Experimental part of this work was done using X-ray CT scanner Metrotom 1500 (see Fig.1) by Carl Zeiss IMT GmbH.

2. RELATED WORK

Threaded and plain gauges are widely used for screw thread inspection during recent decades. They allow complex inspection of threaded fits (NPL, 2010). Gauges are expensive inspection instrument since they are subject to wear and the whole inspection procedure can be long-lasting for large diameter threads (M150 and above). Thread gauges that are proved to be out-of-range by direct measurements can be fit with good master gauges. This situation is typical but gauges and direct measurements are not mutually exclusive methods. Considering the NPL experience (NPL, 2010) one can use both master gauges

and direct measurements to do an elementwise inspection of the thread gauges. First, one should measure pitch, pitch diameter and inner/outer diameters of the thread. Thereupon gauges should be applied to assist the direct measurements. Elementwise inspection is more accurate and can yield numerical results (instead of simple go/no-go answer). The point is direct elementwise measurements do not evaluate the whole surface of the thread therefore form deviations can be overlooked. Gauges can prevent this kind of errors even after elementwise measurements succeeded.

Gauges are unable to separate pitch and diameter deviations. In addition, pitch errors can be hidden by increased pitch diameter. It is traditionally considered practical to use gauges for small threads. As described in NPL notes (NPL, 2010) the primary reason for this discrepancy between gauges and direct measurements is thread form deviations.

Nowadays, a lot of elementwise thread assessment methods have evolved. Their majority is based on coordinate measurement devices and numeric evaluation of the results. A lot of researchers work torwards the improvement of thread inspection. In (Ikonomov et al., 1995) the methos of position and form measurement is proposed based virtual gauges. Carmignato and Chiffre (Carmignato and De Chiffre, 2003) proposed a screw inspection method with a special needle-like probe fitted on a coordinate measuring machine. In (He et al., 2006) authors perform optical inspection of damaged screw threads using CCD camera. Many techniques usually involve different shape analysis algorithms from the field of computer vision and pattern recognition. Robertson and Fisher (Robertson and Fisher, 2001) experimented with 3D scanners and their application to large thread measurement. They examined that it is possible to extract parameters of screw threads from 3D scanned data. However they deal only with inner and outer radii of the thread. In the proceedings (Katz et al., 2009) a method is presented to perform an elementwise inspection of internal threads using laser sensor and CCD camera. Kosarevsky and Latypov (Kosarevsky and Latypov, 2010)

Fig. 1. X-ray CT scanner Carl Zeiss Metrotom 1500

used Hough transformation to extract features from planar sections obtained via profile measuring machines. The mathematics behind these image recognition techniques can be found in (Princen et al., 1992).

In (Perng et al., 2010) a working system is proposed capable of automatic internal thread inspection. It is based on industrial endoscope and computer vision algorithms. However, the main purpose of this system is to detect surface defects and not its geometrical properties. An in-depth overview of classical thread inspection methods is provided in NPL Notes on Screw Gauges (NPL, 2010). Current element-wise thread inspection methods are mainly based on the work of G.Berndt (Berndt, 1940).

Application of high resolution computer tomography (CT) in dimensional metrology has grown popular during the recent years. It has moved from qualitative assessment of workpieces in non-distructive tests to a precise measurement instrument (Kruth et al., 2011).

The accuracy of spatial measurements in these tasks is highly dependent on the geometry and material workpieces. A lot of numeric compensation algorithms are used to achieve the highest possible accuracy and reduce different artifacts of CT scanning.

Traceability of coordinate measurements obtained from computed tomography devices is ensured via special calibration gadgets and procedures. Nowadays these methods received ISO certification. Modern software can extract geometrical features from measured density fields and evaluate their parameters according to ISO norms. To assess the accuracy of CT systems (besides calibration) sets of reference workpieces are used. These workpieces are calibrated on high-precision CMMs and results are compared to the CT data. Recent experiments on GE Sensing & Inspection Technologies (Germany) CT devices show (Luebbehuesen, 2009) the deviation of results for distances and diameters to be within 6 μm. Carl Zeiss

Metrotom 800 X-ray CT scanners can achieve values of $MPE_E = 4.5 + 0.01L\ \mu m$ (Benninger, 2009).

3. INITIAL APPROACH

In this paper, a method of planar sections is used to numericaly assess the quality of screw threads. It allows to reduce the problem of 3D shapes recognition to the finite number of 2D recognition problems. Our method operates on a bundle of planes that contain thread axis. The principal symmetry axis of the CT-scan is considered to be the thread axis. Performing image recognition in each plane a numeric evaluation of thread parameters can be obrained. The planar evaluation algorithm was presented in (Kosarevsky and Latypov, 2010). Using the obtained results one can assess the quality of the measured thread.

Let $f(x_1, x_2, x_3)\ :\ \mathbb{R}^3\ \mapsto\ \mathbb{R}$ be the material density distribution inside the object measured by a CT device and let $\mathcal{D} \subset \mathbb{R}^3$ be the domain where function f is defined. Let us consider a bundle of planes P_α that share a common point $r = (\bar{x}_1, \bar{x}_2, \bar{x}_3)$ ("mass center" of the measured object) as "distinguished" planar sections of the thread. Components r are evaluated as follows

$$\bar{x}_i = \frac{\int_{\mathcal{D}} x_i f(x_1, x_2, x_3)\ dx_1\ dx_2\ dx_3}{\int_{\mathcal{D}} f(x_1, x_2, x_3)\ dx_1\ dx_2\ dx_3},\ i = 0, 1, 2. \quad (1)$$

The thread axis is the common axis of planes P_α which is the principal symmetry axis of the scanned object. Symmetry axes are approximated with the eigenvectors of the covariance matrix

$$A = \begin{pmatrix} \mu_{200} & \mu_{110} & \mu_{101} \\ \mu_{110} & \mu_{020} & \mu_{011} \\ \mu_{101} & \mu_{011} & \mu_{002} \end{pmatrix} \quad (2)$$

where

$$\mu_{ijk} = \int_{\mathcal{D}} W_{ijk} f(x_1, x_2, x_3)\ dx_1\ dx_2\ dx_3,$$
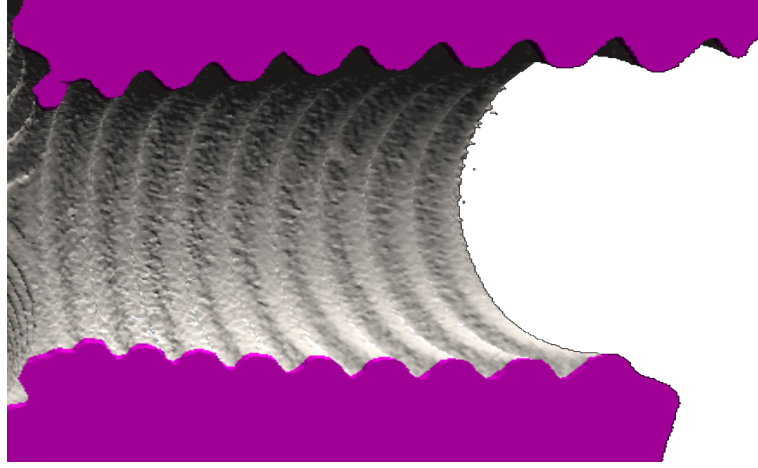$$W_{ijk} = (x_1 - \bar{x}_1)^i\ (x_2 - \bar{x}_2)^j\ (x_3 - \bar{x}_3)^k. \quad (3)$$

Fig. 2. Planar section passing through the axis of M5 thread

The plane P_α passing through the axis of the internal M5 thread is shown in Fig. 2 with the section of the object.

4. ANALYTIC REPRESENTATION OF A SCREW THREAD

In (Nicolson and Fearing, 1991) and (Nicolson and Fearing, 1993) Nicolson et al. proposed a model to represent a basic profile of the metric screw surface. Their model is based on piecewise functions and is effective at finding contact surfaces. In this work a method more suitable for thread recognition is used.

Consider the family of helicoidal surfaces

$$
\begin{cases}
x = D^{-1} w \left(D + |u| H\right) \sin\left(Rv + \pi u\right) \\
y = D^{-1} w \left(D + |u| H\right) \cos\left(Rv + \pi u\right) \\
z = v,
\end{cases} \quad (4)
$$

paramerized by $u \in [-1; 1], v \in [0; V]$ and $w \in [0; +\infty)$.

Assumption $w = D$ yields the surface in Fig.3:

The transform $(x; y; z) \rightarrow (u; v; w)$ can be used to check if some point $(x; y; z)$ belongs to the surface $w = D$. From (4) it follows that $v = z$. Also, $x^2 + y^2 = D^{-1} w^2 \left(D + |u|H\right)^2$ and $x/y = \tan\left(Rv + \pi u\right)$, which gives

$$
\begin{aligned}
u &= \pi^{-1} \left(\arctan\left(y^{-1} x\right) - Rz\right) \\
v &= z \\
w &= D \left(D + |u|H\right)^{-1} \sqrt{x^2 + y^2}.
\end{aligned} \quad (5)
$$

It is easy to see that planar sections of the surface $w = D$ are piecewise linear. Projection on Oyz plane yields $x = 0$, that is $\sin\left(Rv + \pi u\right) = 0$ or

$$
\begin{cases}
Rv + \pi u = \pi k, u = \pi^{-1}\left(\pi k - Rv\right), \\
y = (-1)^k w D^{-1}\left(D + |u|H\right), \\
z = v,
\end{cases} \quad (6)
$$

and u is selected from the $[-1; 1]$ segment by the appropriate choice of the k value.

A bundle of coordinate surfaces intersecting the plane $x = 0$ is shown in Fig.4.

Basic profile (ISO, 1998) of the metric screw thread (Fig.5) is defined by the pitch P, the height of generating triangle H and the nominal diameter D.

According to (ISO, 1998) the values are:

$$
c = \frac{1}{8} H \qquad D_1 = D - 2 \cdot \frac{5}{8} H \qquad D_2 = D - 2 \cdot \frac{3}{8} H \quad (7)
$$

For a metric screw thread the profile angle is $\alpha = 60^o$, so that $\tan\frac{\alpha}{2} = \frac{P}{2H}$ and equations (7) yield:

$$
c = \frac{P}{16 \tan\frac{\alpha}{2}}
$$

$$
D_1 = D - \frac{5}{8} \frac{P}{\tan\frac{\alpha}{2}}
$$

$$
D_2 = D - \frac{3}{8} \frac{P}{\tan\frac{\alpha}{2}}
$$

Any longitudinal planar section of the nominal screw thread is the planar section of the surface Fig. 4, truncated on both sides according to the parameter c.

5. ASSESMENT OF SCREW THREAD PARAMETERS

The overall workflow of our algorithm is as follows:

(1) **Acquire scalar 3D density field.** Authors used Carl Zeiss Metrotom 1500 X-Ray CT scanner to acquire data. Also, several sets of generated data were used to perform an in-depth data analyzis and proove the correctness of our implementation.
(2) **Perform feature extraction.** Apply the thresholding filter. Non-zero values correspond to in-material points. Fig. 6 shows the thresholding result for the scanned external M5 thread with a threshold value of 0.48. The actual range of interest is specified manually.
(3) **Establish thread axis.** Calculate covariance matrix using the equation (2) and determine its eigenvectors.
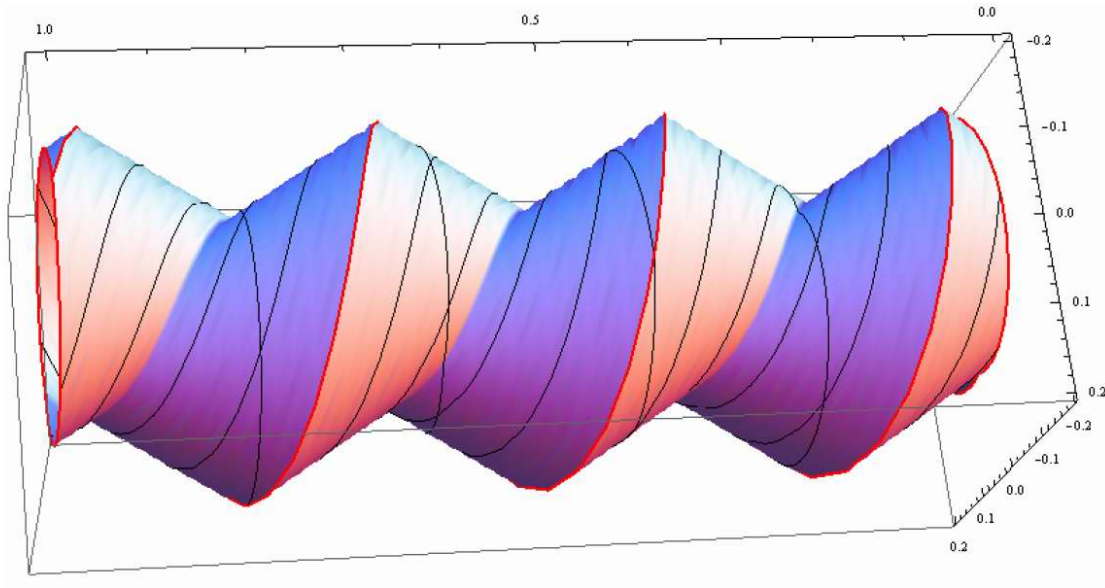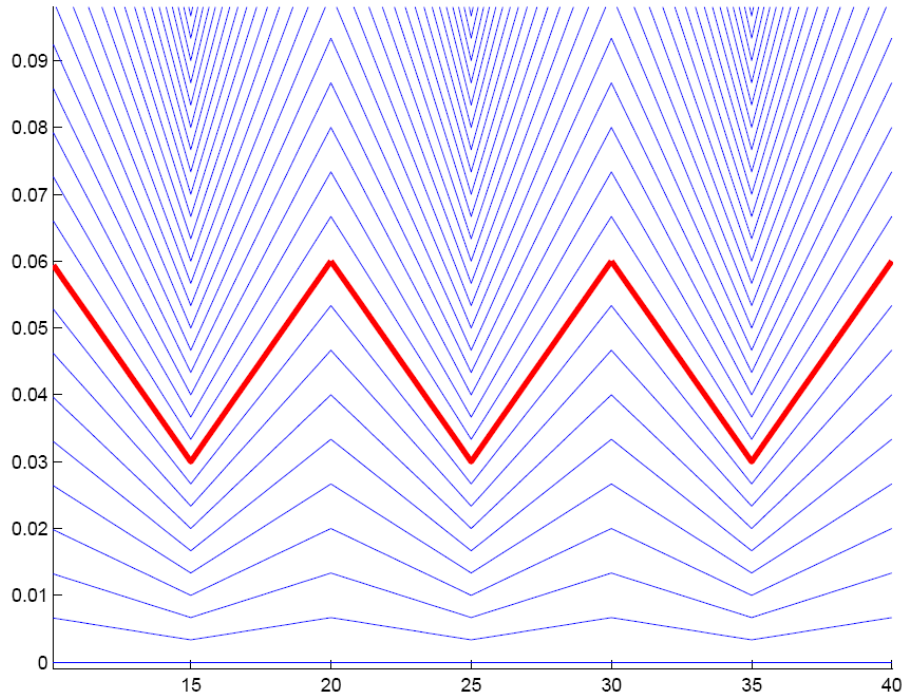
Fig. 3. Surface $w = D$

Fig. 4. Section of the surface $w = D$ at $x = 0$

One of the eigen vectors defines as approximate thread axis, which is a common line for all of the 2D cross section planes.

(4) **Extract isosufrace.** Apply the three-dimensional Sobel filter to determine the points of thread surface. The result of 3D Sobel operator is shown in Fig. 7.

(5) **Generate planar sections.** Fix an arbitrary plane containing the center of mass of the volume and previously determined thread axis. Rotate this plane using a number of uniformly distributed angles in the $0 \dots 2\pi$ range. Clusterize points into buckets corresponding to the closest plane. Every single point can get into a bucket only once.

(6) **Process each planar section (bucket) as described in (Kosarevsky and Latypov, 2010).** Straight lines representing flanks of the thread are obtained via Hough transformation. Sort obtained lines and find intersection points. Intersection points closest to the profile average line are used to fit circles into screw thread groves. Fit circles into the groves. Radii of the circles are chosen so that circles contact the profile close to the pitch diameter, as in the three-wires method.

(7) **Evaluate thread pitch and pitch diameter.** Distances between the fitted circles are used for assessment of screw thread parameters in every planar section.
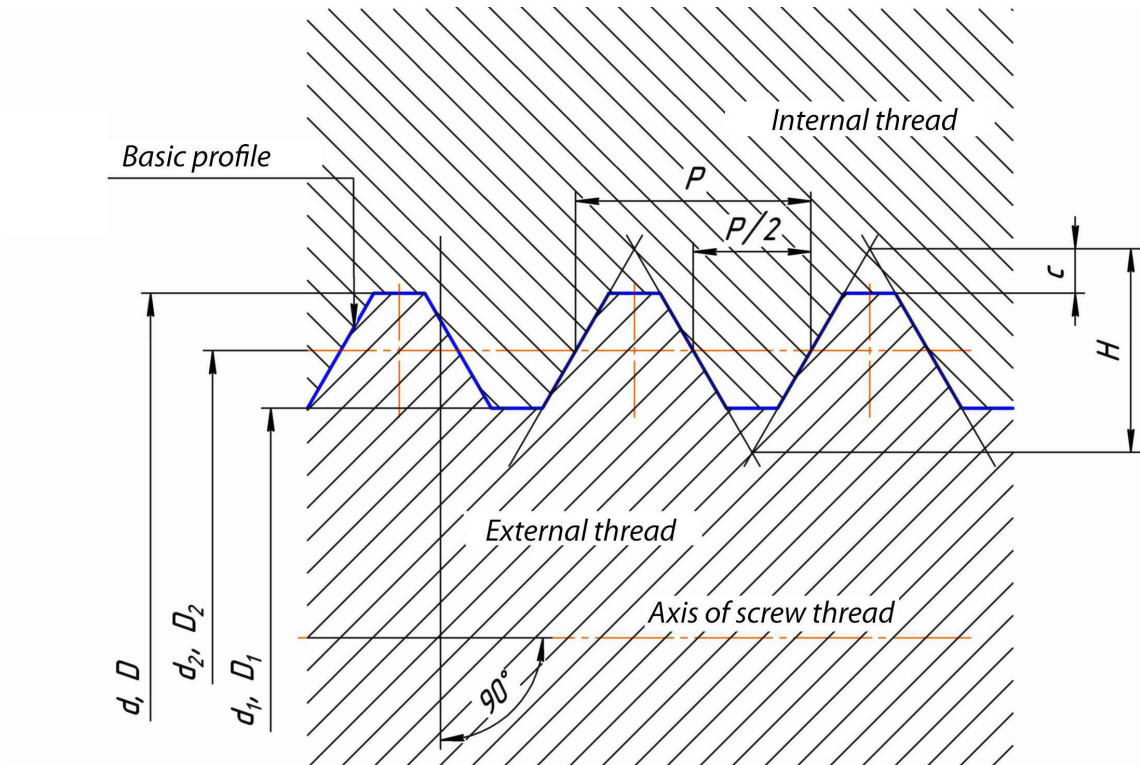
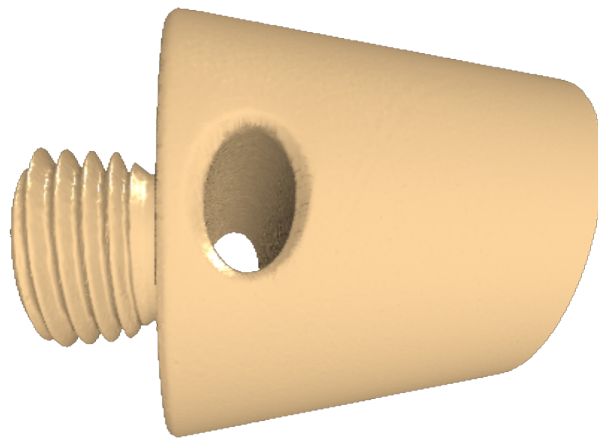Fig. 5. Basic profile of ISO metric screw thread (ISO, 1998)

Fig. 6. M5 screw thread density field after the thresholding filter application
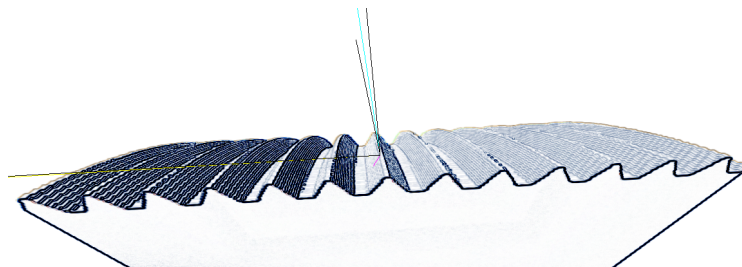

Fig. 7. Results of 3D Sobel operator application to the region of density field

The described procedure can be applied not only to density fields, but also to 3D point clouds. In that case segmentation is already done and one can continue from step 3, using the coordinates of separate points.

Table 1. Numeric results

Thread	Pitch (min.max.), mm	Pitch std. dev., mm
External thread M5	$0.97 \div 1.01$	0.02
Internal thread M5	$0.91 \div 1.07$	0.06
Artificial model	$1.00 \div 1.00$	≈ 0.00

6. EXPERIMENTS AND AUTOGENERATED MODELS

The correctness of the algorithm is checked by processing a number of generated volumes corresponding to some screw threads with specified parameters. The generated volume data is an 1024^3 8-bit three-dimensional array of samples which is essentialy a quantized graph of the χ_S function corresponding to the screw thread. To estimate the precision of the algorithm the generated volume data is corrupted with gaussian noise.

The sample of the generated screw thread model is presented in Fig. 8.

Two aluminum samples with metric screw threads were scanned using Carl Zeiss Metrotom 1500 CT X-ray scanner: internal and external M5 ISO screw threads. Numeric results of screw thread pitch evaluation using 36 planar sections are presented in the table 1.

Significant value of standard deviation for internal thread is due to thicker material and size of the workpiece compared to the external thread workpiece. Standard deviation for our artificial model was below 0.001 mm. However, probability distribution and dependence on the input data need to be assessed more carefully.

Our software was implemented in C++ using Minpack (Min, 1999) optimization library and KHT Sandbox (https://sourceforge.net/projects/khtsandbox) (Fernandes and Oliveira, 2008), the reference implementation of the kernel-based Hough transform for detecting straight lines in binary images. It allows a software implementation to achieve real-time performance even on relatively large images. Fast evaluation of $f(x_1, x_2, x_3)$ gradients was done in a GLSL shader.

Direct evaluation of moments μ_{ijk} using the formula (3) (necessary to establish thead axis), can take significant time at higher resolution. However, in this paper, the problem is not addressed. In case where material density corresponds to a metric screw thead [1] special optimizations methods can be used (Flusser and Suk, 1993).

Eigenvectors of a covariance matrix are calculated using Jacobi eigenvalue algorithm (Flannery et al., 2002).

Presented images were rendered using Linderdaum Engine and Linderdaum Volume Rendering Library.

7. FUTURE WORK

Future work must be undertaken to assess the measurement uncertainty of the proposed algorithm and how noises in the input data and their filtering affect the

results. Measurement uncertainty can be determined via Monte-Carlo trials according to (GUM, 1995) and (GUM, 2008).

It is important to mention that finding values of parameters P and D so that the virtual gauge will fit into the measured thread without intersection will enable direct evaluation of virtual pitch diameter of the thread.

8. CONCLUSIONS

One of the main advantages of the proposed method is that the result is not just a binary "go/not-go", but contains additional numeric data which can be evaluated to determine the exact thread features with deviations. It is important for further technological decisions concerning the production of threaded parts.

One of the main flaws of the proposed methods is the scanning speed of CT equipment. It is required up to one hour of machine time to inspect a single workpiece. However, other types of surface scanning devices (i.e. laser scanning of external threads) can yield improved performance and provide usable 3D point clouds.

9. ACKNOWLEDGEMENTS

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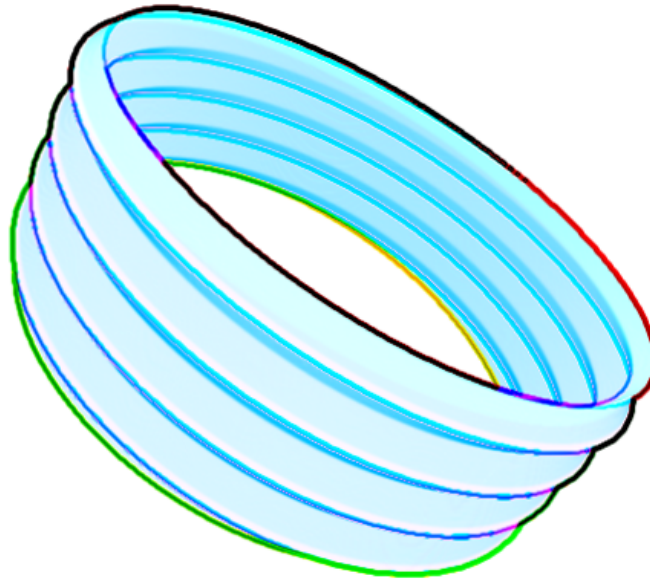[1] Segmented volume contains only binary 0 and 1 without any intermediate values.

Fig. 8. Autogenerated screw thread model

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